

Quantum Manipulation of Ultracold Atoms

RLE Groups

Experimental Atomic Physics Group, MIT-Harvard Center for Ultracold Atoms

Academic and Research Staff

Professor Vladan Vuletic

Visiting Scientists and Research Affiliates

Dr. James K. Thompson

Graduate Students

Adam T. Black, Yu-ju Lin, Igor Teper, Marko Cetina, Andrew Grier, Jonathan Simon

Undergraduate Students

Michael Childress, Huanqian Loh, Brendan Shields, Jacob Bernstein, Thaned Pruttivarasin

Support Staff

Ellenor Emery Barish

1. Collective atom-light interaction: generating single photons on demand

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Atoms isolated in vacuum currently offer the longest storage times for quantum bits, with coherence times of several seconds. However, massive particles are far from ideal for transmitting quantum information in view of the particle velocity and vacuum requirements. In contrast, photons are ideal carriers of quantum information, but are not easily stored. The conversion of quantum states between atomic and photonic representations is thus the subject of much recent interest. Proposed applications include single-photon sources [1], and quantum repeaters for quantum cryptography and teleportation.

In order to achieve coherent coupling between matter and light, the atomic system must appear opaque to the photon. For a single atom, strong coupling to an electromagnetic mode can be achieved in extremely high-finesse optical cavities [2], but the technical requirements are stringent. An alternative approach, that does not require a resonator, is to prepare an entangled state of a many-atom sample (Dicke state [3]) that couples collectively to a free-space electromagnetic mode [4]. To reach high fidelity in the conversion process, the optical density $N\eta$ of the sample must be large, where N is the number of atoms and η is the mode's cooperativity parameter or single-atom optical depth. Pursuing one version of the original idea by Duan, Lukin, Cirac, and Zoller for a conditional single-photon source [1], we have adopted a hybrid approach [5] where an atomic ensemble interacts collectively with a moderate-finesse optical resonator operating in the weak-coupling regime for a single atom $\eta \ll 1$, but in the strong-coupling regime for the sample $N\eta \gg 1$. The latter condition allows for near-unity fidelity in the conversion between atomic and photonic quantum states.

Quantum information stored in a single λ -configuration atom as a superposition of two stable ground states $|0\rangle$, $|1\rangle$ can be converted into an isotropically emitted photon by a spontaneous Raman transition between the two ground states (see Fig. 1b.) Directional photon emission can be achieved by preparing a Dicke state of a many-atom sample, rather than a single atom, and taking advantage of superradiance [3]. Consider an atomic sample inside an optical resonator that is initially prepared in state $|0\rangle$, and Raman scatters photons from an applied pump laser (figure 1a). If a photon is emitted into the cavity, it is not possible to determine which of the N

atoms has made the transition $|0\rangle \rightarrow |1\rangle$. Therefore, the total wavefunction of the sample must be symmetrized with respect to which atom carries the excitation. The initial Raman emission process thus "writes" a collective quantum excitation, or spin grating, into the sample.

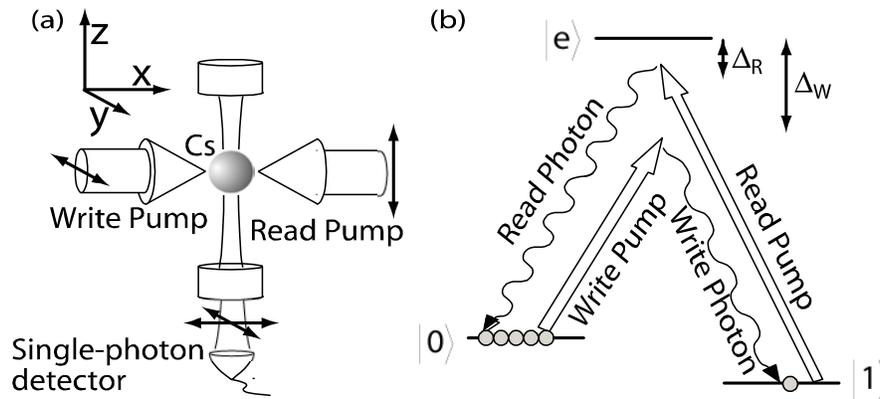


Fig. 1. Setup with optical resonator and pump beams. The photons emitted into the resonator on the Raman transitions $|0\rangle \rightarrow |e\rangle \rightarrow |1\rangle$ and $|1\rangle \rightarrow |e\rangle \rightarrow |0\rangle$ are observed with a single-photon detector. The metastable states $|0\rangle$, $|1\rangle$ can be different hyperfine or magnetic sublevels.

The atoms are then illuminated by a "read" pump beam driving the reverse Raman transition. This field mixes the metastable ground state $|1\rangle$ with the excited state $|e\rangle$, and converts the spin grating into an optical polarization grating. The N terms of the Dicke state constructively interfere to provide an N -fold enhancement of the rate for emitting the second photon, compared to the single-particle emission rate. The atomic sample thus forms the quantum analogue of a phased array of antennas with highly directional emission for appropriate choice of phases between the antennas (see figure 2). The required phase-matching condition between the pumps and emitted photons is equivalent to requiring that the sample be restored to the initial state, or that zero net momentum be transferred to the atom in the combined write-read process. (Any transferred momentum would allow an observer to determine which particular atom scattered the photons, and thus would constitute a form "which-path information" that destroys the necessary quantum interference.)

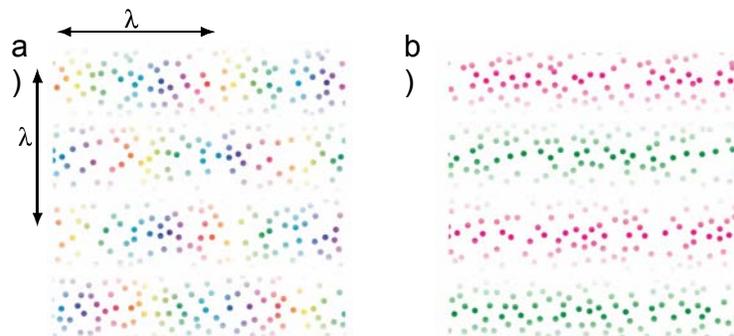


Fig. 2. Phased array of atomic dipole antennas after detection of the write photon (a), and after application of the read pump (b). The dots indicate randomly distributed atoms, the color indicates the phase of the atomic dipole, and the opacity of the dots indicates the strength of coupling to the electromagnetic mode. The standing-wave grating (array of atomic antennas) radiates strongly in the vertical direction.

For a sample of N atoms on the cavity axis, the ratio of the superradiant emission rate into the standing-wave cavity mode and the emission into all of free space is given by $N\eta$, where $\eta = 12F/(\pi k^2 w^2)$ is the single-atom cooperativity, or the fractional emission rate into the cavity for a

single atom. Here F is the finesse of the resonator, w the waist size of the TEM_{00} resonator mode, k the wavenumber of the emitted light, and $\Delta\Omega/4\pi = 2/(k^2w^2)$ the fractional solid angle subtended by the cavity mode. The success probability for emission of the read photon into the resonator, arising from the competition of the superradiant read mode with all other modes, is then given $N\eta/(1+N\eta)$, and approaches unity for a sufficiently large sample with collective cooperativity $N\eta \gg 1$.

Figure 3 demonstrates the ability to write a spin-wave excitation into the ensemble, wait for a programmable time, and then convert the excitation into a photon in a well-defined direction. The write pump is typically applied for 300 ns. After a programmable delay of zero to several μs , the stored excitations are retrieved by switching on the read pump for a few μs . The curves indicate the average time dependence of the emitted write and read photons, with typical read widths (full-width-half-maximum) of 200 ns. The non-collective read signal appears $N\eta$ times more slowly and is not apparent in the plot. No read photons are detected unless the write pump is first applied. In this data set, the average number of write photons scattered into the cavity is approximately 10 photons. The inset demonstrates efficient spin-wave readout, $(57 \pm 15)\%$, at average emitted photon number $0.06 \ll 1$.

We have stored photons in two different atomic internal configurations. For the data presented in figure 3, the states $|0\rangle, |1\rangle$ belong to different hyperfine manifolds. In this configuration, we obtain the lowest backgrounds, and can store single photons, but the recovery efficiency is limited by laser power. We have also stored photons as a superposition of magnetic sublevels within one hyperfine manifold. In this case, the recovery efficiency is higher because the pumps can be tuned close to the atomic transitions, but the backgrounds are higher due to superradiant Rayleigh scattering. For the magnetic sublevel changing configuration, we have observed peak recovery efficiencies of 85% at an average write photon number of $M_w=7$ photons. The magnetic sublevel-changing configuration can be extended to the regime of $M_w \ll 1$ in the future by applying a larger bias magnetic field in order to break the degeneracy of the magnetic sublevels. This should suppress Rayleigh scattering, and allow us to store single photons with near-unity readout efficiency.

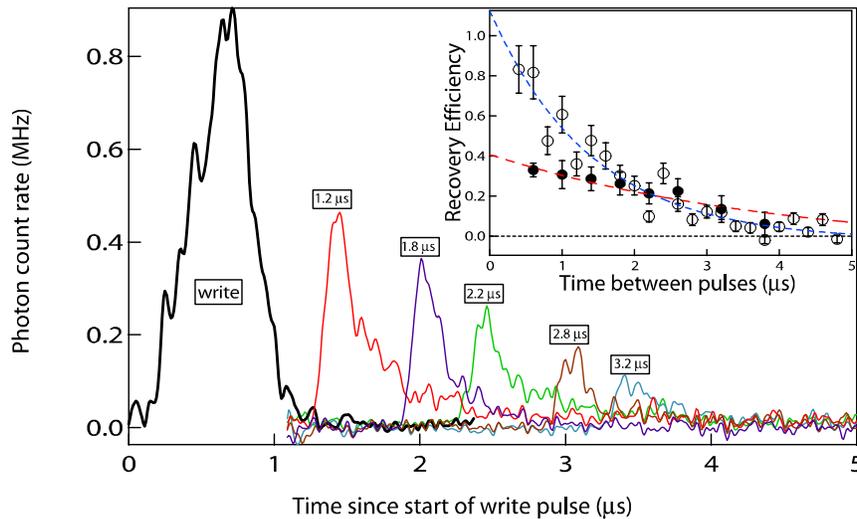


Fig. 3. Averaged write (black line) and read pulses (red line) in the single-photon regime. The different read pulses correspond to different delays of the readout process relative to the write process, and represent different storage times of the single-photon excitation in the sample. Thermal motion of the atoms that destroys the holographic grating that has been written into the sample by the detection of the write photon (inset).

In the example data of Fig. 3, the recovery efficiency R in the hyperfine-changing and magnetic sublevel data decays from peak values 30% and 80% with a characteristic timescale of $3.6 \mu\text{s}$ and $1.3 \mu\text{s}$, respectively. This falloff indicates that the observed read photons are produced via collectively enhanced emission. The time scale is the Doppler decoherence time for the four-photon write-read process. Thermal motion scrambles the phase of each atom's position-dependent coupling to the cavity mode, destroying the collective enhancement of emission.

Doppler decoherence can be virtually eliminated by confining the atoms to the Lamb-Dicke regime using a far-detuned optical lattice. Magnetic field inhomogeneity at $70 \mu\text{s}$ for our current setup is then the leading source of decoherence. An optical lattice would also reduce this decoherence, since trapping the atoms would allow more time for magnetic fields to decay after turning off the MOT. Magnetic-field-insensitive transitions offer the potential to extend the coherence time to nearly a second. This will allow us to experimentally realize a quantum-memory system, and open the way for experiments on long-distance quantum communication and teleportation.

2. Bose-Einstein Condensates on Microfabricated Chips inside an optical resonator: Towards single-atom detection and atomic clocks below the standard quantum limit

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Magnetic traps and waveguides produced by microfabricated structures can trap ultracold atoms and Bose-Einstein condensates in very small volumes. This results not only in fast condensate preparation times and reduced vacuum requirements, but can also be used to produce samples with very large optical depth. Exactly such large optical depth is required for novel nonlinear quantum optics applications, such as single-photon sources, single-photon switches, or spin squeezing of atomic samples by photon detection.

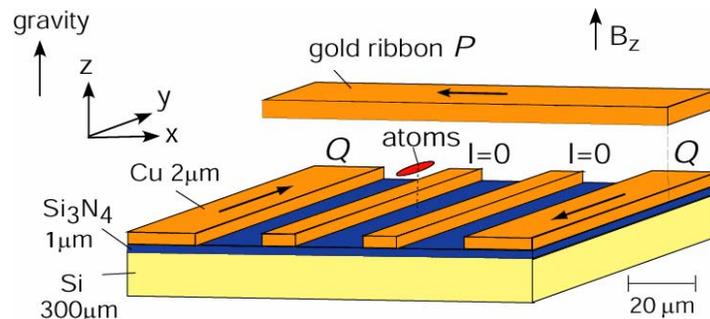


Fig. 3. Microfabricated chip. The outer Cu wires (Q) generate a 2D quadrupole field in the xz plane, the ribbon (P) in combination with an external field gradient creates the confinement along the y direction.

Fig. 3 shows the microfabricated chip that provides radial and axial vibration frequencies of 6kHz , and 70 Hz , respectively, at a distance of $50\mu\text{m}$ from the surface [6]. We typically load 3×10^6 atoms at an initial temperature of $300\mu\text{K}$ into the trap, and evaporatively cool them in 3s to below the condensation temperature of $0.8\mu\text{K}$. An optical resonator supporting a TEM_{00} mode $200 \mu\text{m}$ above the chip surface, and parallel to the long axis of the cigar-shaped atom cloud is attached to the chip support structure (see Fig. 4). The resonator finesse is $F=8000$, corresponding to a photon emission probability of $\eta=13\%$ into the resonator mode. Here η is the mode cooperativity

parameter for a single atom. The collective cooperativity of an atomic sample $N\eta$, that sets the figure of merit for nonlinear quantum optics, can be as high as 10^4 .

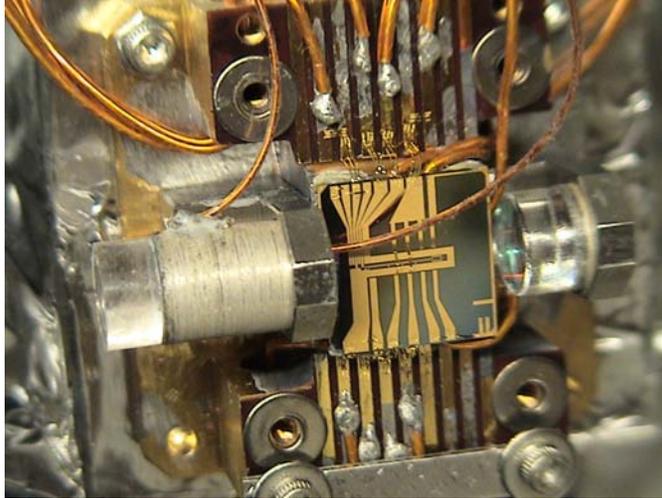


Fig. 4. Microfabricated chip with mounted optical resonator. The resonator mode is aligned $200\ \mu\text{m}$ above the surface of the microchip. The left mirror is mounted on a piezoceramic tube for tuning of the resonance frequency. The resonator finesse is 8000.

In the future, we will use the resonator to detect single atoms trapped above the microchip. This can be accomplished either by fluorescence detection, where the atom is illuminated from the side, and the photons scattered into the resonator are counted on a single-photon detector, or by dispersive detection, where the shift of the resonator frequency due to the presence of the atom is detected. The latter method has the advantage that signal-to-noise per atom is independent of the atom number, and thus a larger number of atoms can be counted with single-atom resolution.

We also plan to use the high optical density of the trapped sample for the preparation of entangled states in order to improve precision experiments and atomic clocks. The best atomic clocks are now at the standard quantum limit (atomic-shot-noise limit) for which the precision scales as \sqrt{N} , where N is the number of atoms composing the clock. This is the highest precision that can be obtained with a system of independent spin- $\frac{1}{2}$ particles. Improved sensitivity should be attainable if one can prepare collective states where the state of one atom depends on the states of the other atoms in the sample (entangled states).

We plan to investigate a spin squeezing technique that would offer precision below the standard quantum limit, thus moving time/frequency measurements towards the more fundamental Heisenberg limit for which the precision increases as N . For example, a typical atomic clock using $N = 10^6$ atoms could potentially be made three orders of magnitude more precise by approaching the Heisenberg limit. In the current system, we hope to realize an improvement of a factor of 10 beyond the shot noise limit.

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Published:

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A.T. Black, J. K. Thompson, and V. Vuletic, "Collective forces on atoms in resonators", *J. Phys. B: At. Mol. Opt. Phys.* **38** (2005) S605-S615 (special issue Einstein year).

Submitted for publication:

A.T. Black, J. K. Thompson, and V. Vuletic, "On-Demand Superradiant Conversion of Atomic Spin Gratings into Single Photons with Very High Efficiency", submitted to *Phys. Rev. Lett.* (April 2005).

V. Vuletic, A.T. Black, and J. K. Thompson, "External-Feedback Laser Cooling of Molecular Gases", submitted to Phys. Rev. Lett., quant-ph/0410168.

Meeting Papers

Presented:

A.T. Black, J. Thompson, H.W. Chan, and V. Vuletic, "Collective laser cooling due to spatial self-organization of classical atoms: From Rayleigh to Bragg scattering" *Workshop on Quantum Gases, Kavli Institute for Theoretical Physics, UC Santa Barbara* (June 2004).

Y. Lin, I. Teper, C. Chin, and V. Vuletic, "Bose-Einstein condensates near room-temperature surfaces", Boulder summer school on "Coherence and Interactions in Atomic and Condensed Matter Physics", University of Colorado (July 2004).

A.T. Black, J. K. Thompson, and V. Vuletic, "Atomic samples in resonators: forces, photons, feedback", XIX. International Conference on Atomic Physics (ICAP 2004, Rio de Janeiro, July 2004).

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Published:

J. K. Thompson, A.T. Black, and V. Vuletic, "Atomic samples in resonators: forces, photons, feedback", XIX. *International Conference on Atomic Physics* (ICAP 2004, Rio de Janeiro, 7/2004), edited by L. G. Marcassa, K. Helmerson, and V. S. Bagnato, pp. 175-183 (AIP Conference Proceedings, Melville, New York 2005).